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MATERIALS COMPATIBILITY AND AGENT OPERATIONAL VALIDATION FOR HALON 1211 REPLACEMENT: PHASES I, II, AND III

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As a result of stratospheric ozone depletion and greenhouse warming concerns, the present halon fire-extinguishing agents will be phased out by 1 January 1994 under an international treaty. The U.S. Air Force has placed a high priority on the development of substitute agents to replace halon fire suppressants. This report describes the assessment of perfluorohexane, one of the candidate substitute agents, through a series of materials compatibility and operational validation testing. The materials compatibility testing was conducted according to applicable Underwriters Laboratories and American Society for Testing and Materials test methods. The testing showed that perfluorohexane is compatible with most elastomers and the composites and electrical components found on aircraft. The operational validation testing incorporated varying climatic conditions, electrical fires, oxygen-enriched fires, and aircraft landing-gear fires. The tests showed that the effectiveness ratio of perfluorohexane to Halon 1211 was approximately 3-3.6 to 1. This suggests that either perfluorohexane must be used in larger quantities during fire situations, or reserved for first response use only. It is recommended that further testing be performed to optimize the nozzle and system for delivery of perfluorohexane.

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PREFACE

This report was prepared by the New Mexico Engineering Research Institute (NMERI), The University of New Mexico, Albuquerque, New Mexico 87131-1376, for the Wright Laboratories, Air Base Fire Protection and Crash Rescue Systems Branch, Tyndall Air Force Base, Florida 32403-6001 under Subtask 2.32, "Materials Compatibility and Agent Operational Validation," Contract F29601-87-C-001. This report covers Phases I, II, and III of that project. A separate report is being written on the Phase IV effort, which is quite distinct from the work discussed here. The WL/FIVCF Project Officer was Dr. Charles J. Kibert; the Principal Investigator at the conclusion of the project was Dr. Robert E. Tapscott. Mr. Michael Lee was the Project Officer during most of the work described herein.

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EXECUTIVE SUMMARY

A. OBJECTIVE

The objectives of the Phase I effort were to review applicable test methods for determining the effects of a haloalkane extinguishing agent on extinguisher and aircraft parts and materials and identify typical flightline fire scenarios for agent validation testing. The agent to be tested was perfluorohexane, the agent selected as a probable replacement for Halon 1211 in Air Force flightline fire protection. The objectives of the Phase II and III efforts were to conduct the tests recommended by the Phase I report. The tests for the Phase II effort, or Materials Compatibility testing, were designed to determine the effects of haloalkanes on extinguisher parts and materials and on aircraft materials and components under varying weather conditions. The Phase III effort was conducted to test the replacement firefighting agents against Halon 1211 with different types of flightline fires.

B. BACKGROUND

The Montreal Protocol and 1990 Clean Air Act Amendments identify halon fire-extinguishing agents as potential stratospheric ozone-depletion chemicals. These chemicals are now scheduled to be phased out of production by the year 1996. In response to these regulations, the United States Air Force has initiated research to identify candidate replacement agents for Halon 1211. As a result of this research, perfluorohexane was selected for further evaluation as a Halon 1211 replacement agent.

C. SCOPE

The scope of this task included testing perfluorohexane with materials and situations involving Halon 1211 usage. This was done to determine (1) whether any compatibility problems existed and (2) the environmental range over which perfluorohexane could be used.

D. METHODOLOGY

The task was divided into three phases: Technology Review and Methodology Development, Materials Compatibility, and Agent Operational Validation. The Materials Compatibility testing was conducted according to applicable Underwriters Laboratories (UL) and American Society for Testing and Materials (ASTM) test methods. The testing in this phase was conducted concurrently with testing at the Underwriters Laboratories and Minnesota Rubber Company to ensure data integrity. The Agent Operational Validation testing was conducted according to the test scenarios outlined in a USAF Test Concept Paper[1]; it was intended to simulate actual firefighting conditions for an accurate comparison of replacement agents and Halon 1211.

E. TEST DESCRIPTION

Standard compatibility and fire tests were used in this evaluation wherever possible. The former tests included immersion testing of elastomers following ASTM procedures. The latter were conducted using outside pan fires with JP-4 jet fuel following methodologies developed in earlier NMERI testing of Halon 1211 candidates.

F. RESULTS

The testing showed that perfluorohexane is compatible with most elastomers, Teflon and silicone rubber being exceptions. It is also compatible with composite materials and electrical components that could be found on aircraft.

The environmental fire testing series showed that perfluorohexane was not as affected by winds as Halon 1211. However, the reverse was true under rainy conditions. The performance of perfluorohexane was slightly reduced in the rain, while Halon 1211 performance was virtually unchanged. Also, the effectiveness of perfluorohexane dramatically improved when tested at -40 °F and reduced at 120 °F, while Halon 1211

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[1]*Halon 1211 Replacement Agent Program, Test Concept Paper,* Air Force Civil Engineering Support Agency, Tyndall Air Force Base, FL, March 1992.

was unaffected. The effectiveness of the perfluorohexane at 120 °F was greatly improved when the application nozzle was changed from a flat spray to a full cone.

The electrical fires showed that perfluorohexane was essentially as effective as Halon 1211 for semienclosed electrical fires. Perfluorohexane was also very effective with enclosed oxygen-enriched fires. Minimal amounts of agent were required to extinguish the fully involved oxygen-enriched fuel fires. Halon 1211 also was effective on these fires and was more effective than the perfluorohexane. The oxygen-enriched tests also showed that when perfluorohexane was applied to an enclosed area, it formed a dense, ground-hugging agent cloud that was very effective in preventing fuel surface reignition.

This testing also showed that the effectiveness ratio between perfluorohexane and Halon 1211 for most tests was 3 - 3.6 to 1. This suggests that perfluorohexane must be either applied in larger quantities or reserved for first-response use only.

G. CONCLUSIONS

BUNA-N nitrile-lined and reinforced butyl rubber hoses should be used for extinguishers and transfer hoses. BUNA-N is also the recommended material for gaskets and seal materials. Teflon and silicone rubber are not recommended; however, Teflon sealant tapes are acceptable for wrapping the threads of removable extinguisher parts. BUNA-N elastomers should also be used for extinguisher sealing materials.

Perfluorohexane is compatible with composite materials and electrical components that could be found on aircraft. Perfluorohexane should not degrade aircraft materials.

H. RECOMMENDATIONS

It is recommended that additional testing be performed to optimize further the nozzle and system for delivery of perfluorohexane.

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LIST OF ABBREVIATIONS AND ACRONYMS

ASTM	American Society for Testing and Materials
NMERI	New Mexico Engineering Research Institute
PVC	polyvinyl chloride
UL	Underwriters Laboratories

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SECTION I
INTRODUCTION

A. OBJECTIVE

The objectives of the Phase I effort were to review applicable test methods for determining the effects of haloalkanes on extinguisher and aircraft parts and materials and identify typical flightline fire scenarios for agent validation testing. The objectives of the Phase II and III efforts were to conduct the tests recommended by the Phase I report. The tests for the Phase II effort, or Materials Compatibility testing, were designed to determine the effects of haloalkanes on extinguisher parts and materials and on aircraft materials and components under varying weather conditions. The Phase III effort was conducted to test the replacement firefighting agents against Halon 1211 with different types of flightline fires that could occur.

B. BACKGROUND

The Montreal Protocol and 1990 Clean Air Act Amendments identify halon fire-extinguishing agents as potential stratospheric ozone-depleting chemicals. These chemicals are now scheduled to be phased out of production by the year 1994 (Reference 1). In response to these regulations, the United States Air Force has initiated research to identify replacement agents for Halon 1211 (Reference 2).

Since any replacement agent would be stored in extinguishers and used to extinguish aircraft fires, agent compatibility with extinguisher and aircraft materials had to be determined. The extinguisher components that were tested included metal cylinder containers, O-rings, valve seat seals, stem seals, dip tubes, and hose material. Aircraft materials, such as electronics, skin and structural materials, wiring and insulation, and engine components, were also tested.

Since the candidates are to replace Halon 1211, a direct-performance comparison criterion was developed to compare the candidates with Halon 1211 accurately. To initiate this comparison, typical fire situations requiring Halon 1211 were identified by the Air Force in a Test Concept Paper (Reference 3). This testing was planned so that the extinguishment performance and limitations of Halon 1211 and perfluorohexane could be directly compared.

C. SCOPE/APPROACH

The scope of this task included testing replacement fire-extinguishing agents with materials and situations involving Halon 1211 usage. The test methods involving the materials identified in the Phase I report (Reference 4) and comprehensive test scenarios developed in the Test Concept Paper to determine the difficulty in making a transition from Halon 1211 to replacement agents were to completed. Standard materials compatibility and fire tests were used in this evaluation wherever possible.

The task was divided into the three phases: Technology Review and Methodology Development, Materials Compatibility, and Agent Operational Validation. The Technology Review and Methodology Development work was completed and documented in the Phase I Letter Report (Reference 4). The Materials Compatibility testing was conducted according to applicable Underwriters Laboratories (UL) and American Society for Testing and Materials (ASTM) test methods. The testing in this phase was conducted concurrently with testing at Underwriters Laboratories and Minnesota Rubber Company to ensure data integrity. The Agent Operational Validation testing was conducted according to the test scenarios outlined in the USAF Test Concept Paper (Reference 3). This testing was intended to simulate actual firefighting conditions for an accurate comparison of replacement agents and Halon 1211.

SECTION II
MATERIALS EVALUATION

A. EXTINGUISHER MATERIALS

A fire extinguisher is designed to fulfill two basic functions: storage of a firefighting agent and efficient discharge of the agent on a fire. In order to satisfy both demands, the extinguisher must be uniquely designed and constructed. Over the years, this design has been tested and modified in accordance with the changing specifications required by qualifying agencies and product users (Reference 5). The finished design for a Halon 1211 extinguisher optimizes both the storage and use capabilities of the extinguisher.

A cylinder-type container with a containment valve is used to store an agent for an extended period. The cylinder is manufactured and pressure-tested to ensure that it can safely store the agent under pressure until ready for use. The containment valve has been designed to contain the agent for extended periods of time and then to open the cylinder and expel the agent. This containment valve includes elastomeric parts that form seals which remain in contact with the agent in the cylinder. The seals used are O-rings, gaskets, and valve stem seats. The polymers used for these seals are formulated so that they are compatible with the agent stored in the cylinder. The materials used in extinguisher construction are listed in Table 1.

Most cylinders are constructed of mild steel, but some manufacturers use aluminum cylinders if the extinguisher is to be used for marine applications (Reference 6). Steel is compatible with Halon 1211 unless moisture is present in the container (Reference 7). Moisture that enters the cylinder with the charging gas, or from improper cylinder filling procedures, can cause the formation of acids, which readily corrode the interior of the cylinder.

TABLE 1. TYPICAL EXTINGUISHER MATERIALS.

Component	Material
Cylinder	Mild steel or aluminum
Elastomeric seals (O-rings, valve stem seals, gaskets)	BUNA-N nitrile rubber
Hoses	BUNA polymers
Dip tube (or siphon tube)	Copper or brass

Elastomeric seals in Halon 1211 extinguishers are manufactured of BUNA-N nitrile rubber.[1] This elastomer is compatible with Halon 1211 but may not be compatible with replacement agents.[2] Several grades of this polymer are available from seal manufacturers. The grades differ in hardness, tensile strength, ultimate elongation, and compression and tensile set. Some formulations will withstand large variations in temperature, matching the requirements of extinguisher-certifying agencies.

The hose used to control the agent as it leaves the extinguisher is manufactured from BUNA polymers that are less resistant to halocarbons than the extinguisher seal material.[1] This decrease in agent compatibility is allowed because the agent normally is not in contact with the hose for an extended period of time.

Another important extinguisher component is the dip tube (or siphon tube). This large-diameter tube is attached to the containment valve and extends downward into the extinguisher cylinder until the end of the tube is 1/4 inch from the cylinder bottom. The dip tube ensures that liquid extinguishing agent, not charging gas, is delivered through the containment valve when it is opened. A manufacturers' survey revealed that these dip tubes are normally constructed of copper or brass (Reference 4).

[1]Personal communication, Paul Huston, Vice President, Government Sales, Amerex Corporation, Trussville, AL, January 1992.

[2]Personal communication, Pete Evanson, Lab Manager, Minnesota Rubber, Minneapolis, MN, January 1992.

Amerex Corporation in Trussville, AL, supplies most of the extinguishers used in the Air Force. The extinguishers addressed by this study are the Model 372 20-pound and Model 600 150-pound units. The Model 600 extinguisher is the standard flightline extinguisher used to protect aircraft.

B. AIRCRAFT MATERIALS

Several types of materials are used in the manufacture of military aircra[illegible]ese include metal structural and skin materials, composite materials, paints and finishes, glass, acrylic or polycarbonate canopies, rubber tires and hydraulic hoses, elastomeric seals (O-rings or gaskets), electronics (printed circuit boards, assemblies, wiring and insulation, coatings, and components), and engine materials (Table 2). The following discussion describes most of the materials found in these categories.

1. Metal Structural and Skin Materials

The aircraft industry has used metals to construct aircraft for many years because of their high strength-to-weight ratio, ease of manufacture, formability, and endurance properties (Reference 8). Most metals used are high-strength steels, aluminum, and titanium. These materials are used throughout the aircraft for structural support, compartmentalization and protection of interior components, and exterior skin construction.

The most vulnerable, or exposed, portion of the aircraft to the application of an extinguishing agent is the exterior skin material. The skin is normally manufactured from an aluminum alloy, although some aircraft have composite skin components. Two aluminum alloys used for this skin material are 2024 T4 and 2024 T5 (Reference 9). These skin materials can be supported by 6061 aluminum alloy support struts (Reference 9). Some skin materials are manufactured with titanium, especially if the aircraft is designed to travel at supersonic speeds or at high altitudes (Reference 10).

TABLE 2. COMMON AIRCRAFT MATERIALS.

Component	Material
Metal structural and skin materials	High-strength steels, aluminum alloys, titanium
Composite materials	Graphite- and boron-epoxy resins
Coatings	Paints, epoxies
Canopies	Glass, acrylic, polycarbonate
Rubber components (hydraulic lines, tires)	Various polymers
Elastomeric seals (O-rings, gaskets)	Various BUNA polymers
Engine materials	Titanium, high-nickel alloys, stainless steels, advanced metals, metal composites, some other composite materials
Electronic components	Electrical circuits, printed circuit boards, wiring, epoxy conformal and potting compound coatings, wiring insulation

2. Composite Materials

Composite materials are currently being tested and manufactured for various applications in the construction of military aircraft (Reference 11). These materials have advantages and disadvantages. Advantages include weight savings of up to 30 percent over metal aircraft components; the ability to design required strength or stiffness properties into the material; the ability to construct large, unjoined assemblies; and the relatively unlimited number of aerodynamic shapes that can be formed (Reference 8). Disadvantages are the high costs of manufacturing and fitting the materials, the length of time to manufacture the material without automation, and structural problems not found in metals (Reference 8). Since these materials are being used more frequently in the design of military aircraft, they are considered in this study.

Several types of composites can be manufactured. The most common composites used in military aircraft are graphite-epoxy and boron-epoxy (Reference 11). These materials are used mainly for aircraft controls surfaces, such as wing spoilers, ailerons, flaps, and elevators and rudders (Reference 12). Some state-of-the-art aircraft, however, use composite materials extensively in their construction. Although two of these types of aircraft, the B-2 and the A-12, have been phased out of production by defense funding cuts mandated by Congress, many military aircraft now in service still use composite components (Table 3) (Reference 11).

Military aircraft now using composite materials include the following: A-7, AV-8B, B-1, B-2, C-5A, C-130, C-141, E-2A, E-2C, F/A-18, F-4, F-5, F-5A, F-5E, F-14, F-15, F-16, F-111, F-111B, F-117A stealth fighter, KC-135, QC SEE, S-3A, T-38, and the T-39. Future aircraft modifications and prototypes now being planned will use composites extensively. The V-22 Osprey and the A-6 are being fitted with wings made entirely of composite materials (Reference 8). The Air Force has developed a new Advanced Tactical Fighter, the YF-22, in which composites will be extensively used (Reference 8).

Any replacement extinguishing agent will have to be compatible with these materials. Liquid extinguishing agents could react with the bonding epoxy in composites causing delamination or debonding.

3. Coatings

Aircraft skin is coated or painted for protection from the environment. These coatings are resistant to rain, hail, corrosion, and hot and cold temperature extremes (Reference 10). These coatings do not contribute material strength; however, if the coating were removed, the underlying material would be more susceptible to chemical or environmental attack. To decrease this vulnerability, the extinguishing agent should be tested with coating materials.

TABLE 3. ADVANCED COMPOSITES IN MILITARY AIRCRAFT.

Aircraft Model	Material	Component	Status[a]
A-4	Boron-epoxy, Graphite-epoxy	Flap	1
	Graphite-epoxy	Horizontal stabilizer, speed brakes	2
A-7	Graphite-epoxy	Speed brake	1
A-7D	Graphite-boron-epoxy	Outer wing panels	2
A-9E	Graphite-epoxy	Rudder	1
A-12	Graphite-epoxy	Most of aircraft	1
A-37B	Graphite-epoxy	Outer cylinder landing gear, trunnion, landing-gear side brace	2
AV-8B	Graphite-epoxy	Wing-box skins, forward fuselage, horizontal stabilizer elevators, rudder, over-wing fairing, ailerons, flaps	2
B-1 (original)	Boron-epoxy	Torque-box cover skin, longeron	1
	Hybrid boron-epoxy, Graphite-epoxy	Vertical stabilizer, horizontal stabilizer, wing slat	2
	Gl-epoxy	Torque-box cover skin	1
	Graphite-epoxy	Torque-box cover skin	1
		Secondary airframe structures, leading and trailing edge flaps, weapons bay and avionics doors	2
B-2	Carbon-epoxy	Most of aircraft	3
C-5A	Boron-epoxy, Gl-epoxy, Graphite-epoxy	Nose radome, wing leading edge, wing trailing-edge flaps, engine nacelles, pylons, cargo doors, landing-gear fairings, troop-compartment floor, aft fuselage panels	3
	SiC-Al	Wing box	1
C-130	Boron-epoxy	Center wing box	1
C-141	Hybrid graphite-epoxy and Gl-epoxy	Aft cargo-door cover (petal door)	2
E-2A	Gl-epoxy	Rotating radome	3
E-2C	Gl-epoxy	Inboard vertical stabilizer fin	1

[a]1 = experimental; 2 = prototype development; 3 = production

TABLE 3. ADVANCED COMPOSITES IN MILITARY AIRCRAFT (CONTINUED).

Aircraft Model	Material	Component	Status[a]
F/A-18	Graphite-epoxy	Wing skins, horizontal tail box, vertical tail box, wing control surface, tail control surface, leading-edge extension of wings, horizontal actuator cover, dorsal covers, landing-gear doors, rudders, fixed trailing edge, speed brake	3
F-4	Boron-epoxy, boron-PI, Graphite-PI	Rudder	1
F-5	Graphite-epoxy	Horizontal stabilizer	2
		Fuselage component	3
F-5A	Graphite-epoxy	Speed-brake door, landing-gear door, wing slat, rudder, horizontal tail, wing leading edge	2
F-5E	Graphite-epoxy	Trailing-edge wing flap	1
F-14	Boron-epoxy	Horizontal-stabilizer skins	3
	Graphite-epoxy	Main landing-gear door, vertical stabilizer	2
F-15	Hybrid boron-graphite, Gl-epoxy, Graphite-epoxy	Wing	1
	Boron-epoxy	Vertical tail, horizontal tail, rudder, stabilizer skins	3
	Graphite-epoxy	Speed brake	3
F-16	Graphite-epoxy	Empennage skins, vertical fin, fin leading-edge skins, rudder tail skins, horizontal tail skins, forward fuselage	3
F-111	Boron-epoxy	Horizontal tail	2
	Boron-epoxy and Boron-Al	Fuselage section	2
	Graphite-epoxy	Under-wing fairings	3
	Hybrid graphite-epoxy, Boron-epoxy, Boron-Al, Gl-epoxy	Aft fuselage centerbody	1
F-111B	Boron-epoxy	Wing box	1
F-117A	-----	Most of aircraft	3
KC-135	Gl-epoxy	Winglet	1

[a]1 = experimental; 2 = prototype development; 3 = production

TABLE 3. ADVANCED COMPOSITES IN MILITARY AIRCRAFT (CONCLUDED).

Aircraft Model	Material	Component	Status[a]
QCSEE	Graphite-PI	Inner cowl	2
S-3A	Graphite-epoxy	Spoilers	3
T-38	Graphite-epoxy	Aileron trailing edge Horizontal stabilizer	2 3
T-39	Boron-epoxy	Wing box	2
V-22	-----	Wings	1
YF-22	-----	Most of aircraft	1

[a]1 = experimental; 2 = prototype development; 3 = production

4. Canopies

Aircraft canopies are constructed to produce high visibility for the pilot and provide a high-strength component resistant to the performance stresses occurring in flight. Canopies are normally constructed of glass, acrylic, or polycarbonate materials.[1] If an agent is incompatible with these materials, the canopies could become etched or cracked, producing flaws that could cause failure.

5. Rubber Components

Aircraft hydraulic lines and tires are constructed from various grades of rubber or polymers that could be susceptible to chemical attack. Hydraulic line assemblies provide the necessary flight control for many major critical aircraft components. Pneumatic tires, some with composite material belts, are included on all

[1]Personal communication, Theodore Reinhart, Chief, Materials Engineering, Wright-Patterson Air Force Base, OH, November 1991.

aircraft landing gear. These types of polymers can readily lose plasticizers if subjected to certain types of chemicals for extended periods (Reference 13).

6. Elastomeric Seals

Multiple locations throughout an aircraft have elastomeric seals (Reference 10). Components such as O-rings and gaskets are commonly used to produce positive seals in pressurized systems. The firefighting agent could contact and penetrate to some of these components if the agent were applied in large quantities or a concentrated agent stream were directed toward the assembly containing the component. Most of these seals are oil- and lubricant-resistant BUNA polymers.

7. Engine Materials

Military aircraft are powered by large turbine engines that can produce thousands of pounds of thrust. These engines are constructed of titanium, high-nickel alloys, stainless steels, and advanced metal alloys and metal composites (Reference 14). Some newer engines have metal matrix composite materials (Reference 8). The turbines are composed of several rows of circular fan blades that are relatively thin and fragile. These blades are designed to withstand the extremely high temperatures that can be generated in engine combustion chambers. Since most aircraft fires occur in the engine or engine compartment, the fragile blade materials should be tested for compatibility with any replacement agent. This testing should be conducted at engine operating temperatures.

8. Electronic Components and Wiring

The largest potential compatibility problem could be applying the agent to sensitive electronic components. These components include printed circuit boards that contain sensitive electronic components such as transistors, resistors, amplifiers, power supplies, etc.[1] Electronic components are normally protected from moisture and contaminants by epoxy conformal coatings, or potting compounds, that either partially or completely shield the components.[2] These components and their supporting wiring could be very susceptible to chemical attack from incompatible agents.

Wiring throughout the aircraft and the insulation used to protect or electrically shield the wiring are also subject to chemical attack. Insulation for wiring is usually made of a PVC-based (polyvinyl chloride) polymer that could lose its plasticizer if an incompatible agent were applied. Electrically conductive agents would also be a problem and could cause shorting of wiring or circuit boards.

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[1]Personal communication, Theodore Reinhart, Chief, Materials Engineering, Wright-Patterson Air Force Base, OH, November 1991.

[2]Personal communication, John Pignato, Applications Manager, 3M Corporation, Engineering Fluids and Systems Laboratory, St. Paul, MN, February 1992.

SECTION III

MATERIALS COMPATIBILITY LABORATORY TESTING

A. BACKGROUND

A preliminary literature and professional search was completed to determine what types of materials compatibility tests would be applicable in this testing program (Reference 4). This analysis is documented in the Phase I report for this project. Several UL and ASTM standardized tests were found and were recommended in this report (Reference 4). Each of these tests was completed to determine the compatibility of perfluorohexane with a variety of materials. The UL tests were taken from UL 1093. The specific tests conducted from UL 1093 were No. 28: 30-Day Elevated Temperature Limits Test; No. 29: High-Temperature Limits Test; No. 30: Temperature Cycling Tests; and No. 47: Gasket and O-Ring Tests. The ASTM tests included ASTM D 471: Rubber Property - Effect of Liquids; ASTM D 412: Rubber Properties in Tension; and ASTM D 2240: Rubber Property - Durometer Hardness.

The materials chosen for testing were those that could be subjected to contact from perfluorohexane under storage and firefighting conditions. These materials included various extinguisher parts, such as elastomeric seals, and various aircraft parts (composite materials, electronics, metals, etc.).

Most of the compatibility tests were conducted at NMERI (with verification tests conducted at other laboratories). Some materials tests, however, were either already completed by other competent laboratories or were better suited to be conducted at certification laboratories.

If the compatibility information used in the testing program had been obtained from literature or previous laboratory results, the test methods were verified and the results checked for accuracy. The manufacturer of perfluorohexane, 3M Corporation, had already conducted several materials compatibility tests with materials that would be tested in this program (Reference 13). The data from their tests were verified and used in this evaluation.

It was also determined that the UL 1093 extinguisher compatibility testing should be conducted by the laboratories at UL. This was a cost effective method of achieving certifiable testing for this part of the testing program.

B. TEST PROCEDURES

The following tests were either completed by NMERI, UL, or 3M Corporation. All tests completed were standardized and followed written and established procedures.

1. UL 1093 Extinguisher Testing

These tests were designed to simulate the extreme and normal conditions to which the fully charged handheld extinguisher could be subjected during storage. The extinguisher was required to maintain a certain level of performance after it had been cycled through these environmental conditions. The following UL tests were conducted using UL 20-pound extinguishers with perfluorohexane as the extinguishing agent.

a. <u>UL 1093, No. 28: 30-Day Elevated Temperature Test</u>

A fully charged extinguisher was conditioned at 120 °F for 30 days and then checked for leakage. No leaks were allowed for the extinguisher to pass.

b. <u>UL 1093, No. 29: High-Temperature Exposure Test</u>

A fully charged extinguisher was conditioned at 175 °F for 7 days. If the extinguisher did not rupture, the test was a success.

c. <u>UL 1093, No. 30: Temperature Cycling Tests</u>

A fully charged extinguisher was conditioned at the minimum storage temperature of -65 °F for 24 hours, at 120 °F for 24 hours, at -65 °F for

24 hours, and finally at the minimum storage temperature (70 °F) for 24 hours. The extinguisher was then checked for leakage.

d. UL 1093, No. 47: Gasket and O-Ring Tests

In these tests, the gaskets and O-rings in the extinguisher were tested for tensile strength, elongation, maximum set, hardness, and compression set properties before and after they had been exposed to the extinguishing agent.

2. ASTM Laboratory Tests

Although the UL tests are mainly designed to test the integrity of the extinguisher as a whole, tests were needed to test directly the compatibility of the weakest component, the elastomeric seals, with the agent. The ASTM standardized tests are designed to complete this type of testing.

Sample elastomers from two manufacturers were tested. Minnesota Rubber Co. supplied flat stock samples of 503A BUNA-N, 514A Fluorel (Viton), 559PE EDPM (ethylene propylene), and C2528EK EDPM (ethylene propylene). O-rings of the materials S604 silicone, E893-80 EDPM (ethylene propylene), N304 nitrile (BUNA-N), and 215TFE (virgin Teflon) were purchased from Parker Seals.

The tests with Minnesota Rubber Co. elastomers were duplicated at the laboratory at Minnesota Rubber Co. so that the results could be verified by an independent source. Tests of samples 503A, 514A, and 559PE were conducted using the same ASTM methods as the NMERI testing.

The following ASTM tests were completed using perfluorohexane:

a. ASTM D 471, Rubber Property - Effect of Liquids

In this standard, elastomers were immersed directly in the extinguishing agent at the service temperature (room temperature) for a series of immersion periods. The specimens were checked for changes in mass, volume, dimensions, tensile strength, ultimate elongation, and hardness during and after immersion. The NMERI samples were checked at immersion periods of 70, 166, and 670 hours.

In accordance with this standard, The NMERI tests were conducted with 250-milliliter graduated cylinders specially modified so that the samples could be immersed without touching each other or the sides of the container. Glass joint sealing caps (with clamps) were also added to the tops of the cylinders to ensure that none of the perfluorohexane evaporated during the immersion period.

In the NMERI tests, The Minnesota Rubber Co. samples were cut into the two sample sizes and shapes required by the two separate immersion tests specified in this standard. In the first test, the samples were cut into 1- by 2-inch specimens; three specimens were cut from each of the four elastomer samples. These specimens were tested for changes in mass, volume, and dimensions. A Fisher Model XD-8K electronic balance was used to weigh each specimen before and after the immersion periods to determine both mass and volume changes. The volume change method consisted of weighing the specimens in a water bath. The dimensional changes were measured with Craftsman Model 40181 graduated calipers. These samples were checked at 70, 166, and 670 hours.

In the second NMERI test series, the samples were cut with a certified ASTM Die C, dumbbell stamp cutting die required for tensile testing. Three specimens were cut from each sample and immersed in the same modified, graduated cylinders used in the first test. The immersion period for this second test was 670 hours. These samples were tested for changes in tensile strength, ultimate elongation, and hardness.

The Parker Seals O-rings were also tested in the first NMERI test series in which mass, volume, and dimensional changes were recorded. The second series of tests could not be conducted since only O-ring samples were available.

b. ASTM D 412, Rubber Properties in Tension

The specifications in this standard were meant to be a companion to ASTM D 471. This standard specified the size and shape of the specimens in the tensile tests and specified parameters for the test.

c. ASTM D 2240, Rubber Property - Durometer Hardness

This test method was used to measure the durometer hardness of the elastomers and composite materials subjected to immersion in perfluorohexane. The test instrument recommended for softer materials, like elastomers, was the Type A durometer. The Type D durometer was used to measure the composite material hardness. This was the method used in conjunction with ASTM D 471 for the elastomer tests.

3. 3M Corporation Laboratory Tests

Extensive immersion materials compatibility studies with perfluorohexane and other perfluorocarbon liquids have been conducted by the laboratories at 3M Corporation. The method of testing was Soxhlet extraction. Materials were placed in a Soxhlet extractor and exposed to pure, boiling perfluorohexane for extended periods of time. Boiling the agent removes the impurities and concentrates the chemical liquid so that "worst-case" exposure studies can be conducted. This method is also used to study long-term agent effects.

Various types of materials were tested in this manner. Many types of metals, elastomers, composite materials, electrical components, potting compounds, etc., were extensively tested in the Soxhlet extractor. The results of this testing are included in this report.

4. Composite and Hose Materials Tests

A section of a B-2 aircraft wing, Fiberite T300/934 composite material, was cut into specimen strips and immersed in perfluorohexane. The containers used for this testing were 20-pound extinguishers that were manufactured with a top opening large enough to accept the extinguisher head/valve assembly from a 150-pound extinguisher. Four extinguishers were used, each filled two-thirds full with 8 liters of perfluorohexane. The specimen strips were immersed in the perfluorohexane by dropping them into the fluid. Three extinguishers were sealed with the 150-pound extinguisher head/valve assemblies; one extinguisher was sealed with a fabricated head, the fittings of which were open to the atmosphere. The extinguishers were then placed outside and exposed to ambient weather conditions for two weeks. The extinguisher temperature during this period ranged from 58 to 112 °F and varied as the ambient temperature changed. The extinguisher temperature was higher in the upper temperature ranges due to radiant heating effects. The hardness of the specimens was checked before and after the immersion period with a Type D durometer.

No formal testing was conducted with the extinguisher hose or hose gasket materials; however, informal tests were conducted throughout the Agent Operational Validation testing program. The hoses remained attached to the 150-pound extinguishers (while perfluorohexane filled the hose) in both fully charged (pressurized) and noncharged conditions. The hoses were left in these conditions for periods of approximately 12 to 720 hours and then drained. Neither discoloration of the perfluorohexane nor degradation of hose or hose gasket materials was observed.

C. TEST RESULTS

1. UL 1093 Extinguisher Tests (Reference 15)

The 30-day elevated temperature test was run on two sample extinguishers pressurized to 195 lb/in.^{2} operating pressure conditioned at 120 °F for 30 days. No loss of pressure or weight of the samples was observed following this exposure.

The high temperature exposure test conditioned two sample extinguishers pressurized to 195 lb/in.^{2} for 7 days at 175 °F. No rupture or leakage occurred.

In the temperature cycling test, two sample extinguishers pressurized to 195 lb/in.^{2} were conditioned alternatively for 24 hours each at -65 °F, 120 °F, -65 °F, and 70 °F. Examination showed that both extinguishers had loss of pressure and weight. One sample lost 0.11 lbs and the other 0.01 lbs.

The results of the O-ring tensile and elongation test on the Compound 503A O-ring are shown in Table 4.

2. ASTM Laboratory Tests

These tests were conducted both at NMERI and the Minnesota Rubber Co. laboratories, according to the methods required by specific ASTM tests. The results from both test sets were comparable and verified each other.

The tests conducted included immersing the elastomer samples in perfluorohexane for specified periods of time and measuring the changes in mass, volume, dimensions, tensile strength, ultimate elongation, and hardness. The results are shown in Table 5 for the Minnesota Rubber elastomers. Results of the Parker Seals testing are shown in Table 6.

None of the Minnesota Rubber elastomers showed any appreciable change in any of the properties tested. A 0 to 10 percent loss rate is acceptable in materials testing. All of these elastomers would be compatible with perfluorohexane, with the possible exception of C2528EK. The C2528EK elastomer did show some loss in tensile strength, and a 20 percent loss is considered undesirable.[1] This elastomer was specially blended for related agent testing and would not be available, due to its high production cost, for regular distribution.[1]

[1]Personal communication, Peter Evanson, Lab Manager, Minnesota Rubber, Minneapolis, MN, March 1992.

TABLE 4. UL O-RING TENSILE AND ELONGATION TESTS.

Property	Measured Value
As Received	
Average Tensile Strength (lb/in.^{2})	1793
Average Elongation (percent)	310
After 30-Day Exposure to Perfluorohexane Liquid	
Average Tensile Strength (lb/in.^{2})	1633
Average Tensile Strength (percent of original)	91
Average Elongation (percent)	210
Average Elongation (percent of original)	68
After 30-Day Exposure to Perfluorohexane Vapor	
Average Tensile Strength (lb/in.^{2})	1603
Average Tensile Strength (percent of original)	89
Average Elongation (percent)	220
Average Elongation (percent of original)	71

TABLE 5. ASTM D471 AND D412 MATERIAL COMPATIBILITY TESTING.[a]

Minnesota Rubber Elastomer	Mass (%)	Volume (%)	Dimensions (%)	Tensile Strength (%)	Elongation (%)	Hardness (%)
503A (BUNA-N)	-1.1	+2.2	+0.7	-6.7	+0.2	-2.8
514AD (Viton)	+1.6	2.8	+1.2	-8.0	+0.2	-4.2
559 PE EDPM)	0.0	+3.2	+1.1	+3.0	-0.1	-2.0
C2528EK (EDPM)	-1.0	+3.2	+1.1	-19.2	-4.5	-1.1

[a]Property changes of elastomers immersed in perfluorohexane.

TABLE 6. ASTM D471 MATERIAL COMPATIBILITY TESTING.[a]

Parker Seal Elastomer	Mass (%)	Volume (%)	Dimensions (%)
N304 (nitrile)	+2.6	0.0	-1.5
E893-80 (EDPM)	-2.4	0.0	-1.7
S604 (silicone)	0.0	0.0	-0.1
215TFE (Teflon)	+7.7	0.0	-0.2

[a]Property changes of elastomers immersed in perfluorohexane.

In the Parker Seal O-Ring testing, elastomers were chosen that were expected to pass (E893-80 EDPM nitrile, N304 nitrile, or BUNA-N nitrile rubber) and that were not expected to pass (S604 silicone and 215TFE virgin teflon).[1] The S604 elastomer did not exhibit any appreciable loss in measured properties but was soft and pliable (indicating a loss of hardness or tensile strength); a white residue had formed on the material after the immersion test. Similarly, the 215TFE elastomer did not show unacceptable losses in the measured properties, although fluid had been absorbed into the specimens, increasing the mass. This absorption is an expected occurrence since the Teflon elastomer and the perfluorohexane are both fluorochemicals and should not be compatible with each other. Both the E893-80 and N304 elastomers showed no unacceptable loss in properties. However, the E893-80 elastomer was stiffer after the immersion period, while the N304 elastomer retained its original pliability.

3. 3M Corporation Laboratory Tests

Several compatibility tests have already been conducted at 3M Corporation with various types of materials (Reference 13). These materials include metals, elastomers, plastics, epoxies, conformal coatings, and electronic components. These materials were immersion tested with the Soxhlet extraction method. Some of the tests were conducted with perfluorohexane and some with other, related

[1]Personal communication, Bill Collins, Parker Seals, Technical Service Department, Lexington, KY, February 1992.

perfluorochemicals. Since all the perfluorochemicals used were essentially the same, with minor formulary changes, the data could be used interchangeably.[1]

The metals tested were aluminum, magnesium, stainless steels, copper, beryllium, and a beryllium-copper alloy (98 percent copper). This was a 10-day exposure test conducted at the boiling temperature of perfluorohexane. All the metals passed this test; however, the copper became a little discolored. The report (Reference 13) stated that this discoloration could have been caused by atmospheric moisture, rather than the perfluorohexane.

The elastomers tested in six-month exposure tests conducted at 167 °F included butyl, chloroprene, fluorinated polymers, and silicone. Changes in tensile strength, Shore A hardness, weight, volume, and appearance were recorded. All the elastomers except the fluorinated polymers passed these tests.

Plastics were also tested. The types of tested materials included polychlorotrifluoroethylene, polytetrafluoroethylene, polypropylene, nylon, and polyethylene. These were also six-month exposure tests at 167 °F, and the same properties measured in the elastomer studies were recorded. The polypropylene and the polyethylene became too brittle to test after the immersion period, but the other plastics had no appreciable property changes.

O-rings were tested in two separate tests, one conducted for 7 days at 230 °F and the other for 12 weeks at 212 °F. The elastomers tested included butyl, chlorosulfanated polyethylene, chloroprene, nitrile, silicone, polysulfide, and fluorinated compounds. No appreciable property changes in the elastomers were observed except for the silicone and fluorinated materials. These elastomers showed appreciable changes in weight and volume.

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[1]Personal communication, John Pignato, Applications Manager, 3M Corporation, Engineering Fluids and Systems Laboratory, St. Paul, MN, February 1992.

Several epoxies, conformal coatings, and electronic components that would be found on aircraft electrical systems were also tested. In these tests, five out of six epoxies, a polyimide, a silicone conformal coating, and two polyesters were favorably tested. Also, all electronic components (including printed circuit boards), whether tested in the electrically charged or uncharged condition, were found to be compatible (Reference 16).

4. Composite and Hose Materials Tests

The Fiberite T300/934 composite material was immersion tested, and changes in hardness (Shore D) were recorded. The results are shown in Table 7. No changes were observed in the hardness of this material.

The informal hose observation testing was conducted during actual field operating conditions that would be expected if the perfluorohexane were used on the flightline. These tests showed that the perfluorohexane did not become discolored while being held in the hoses, which suggests that no deterioration of the hoses occurred. Also, observations of the hoses and gaskets showed that there was no unusual deterioration of these materials.

TABLE 7. AIRCRAFT COMPOSITE MATERIAL HARDNESS TESTING.

Sample No.	Original Hardness	Final Hardness	Change (%)
1	88	89	+1.1
2	90	92	+2.2
3	90	89	-1.1
4	92	91	-1.1
5	90	89	+1.1
6	90	90	0.0
7	92	89	-3.0
8	90	91	-1.1

SECTION IV
AGENT OPERATIONAL VALIDATION TESTING

A. BACKGROUND

The Air Force firefighter training program developed several fire scenarios modelled after actual fire scenario conditions. Personnel at the HQ AFCESA/DFO Air Force Fire Protection Branch were involved in determining typical fire scenarios. The suggestions made by these personnel included spill fires (1-dimensional), engine mockup fires (3-dimensional flowing and nonflowing fuel fires), mixed-fuel fires (hydraulic oils, aircraft components), electrical-component-overload fires, and oxygen-enriched aircraft interior fires. Some of these fires were to be conducted under various environmental conditions, for example, wind, rain, and operating temperature extremes.

These scenarios were incorporated into a Test Concept Paper (Reference 3) and were intended to be used as guidelines for the testing program. The tests described in the Test Concept Paper were not standardized UL 1093 or UL 711 fire tests; however, some parts of the UL standardized tests were modelled in the prescribed testing scenarios. All tests within the Test Concept Paper were to be completed in this testing program.

The testing assigned to NMERI (within the Test Concept Paper) included the conduct of three-dimensional running fuel fires (11.5 ft^3 nacelle) under various environmental conditions. These tests were conducted in calm conditions, in both 10-mph crosswind and 10-mph tailwind conditions, and at temperature extremes of -40 °F and 120 °F. Moisture conditions of 1 inch/hour rainfall were also tested. Other tests included aircraft wheel gear (complete with tire) and spraying hydraulic oil fires, semienclosed electric motor fires, and semienclosed oxygen-enriched fuel fires.

B. TESTING FACILITIES

The testing facilities are located on Kirtland Air Force Base at the Civil Engineering Research Facility (CERF). The tests were conducted inside a wind-fence enclosed site (Figure 1). The wind fence was constructed mainly of TENAX Riparella mono-oriented net material. The test site consisted of a pair of wind fences oriented in concentric circles to maximize the wind abatement effect. The wind fences totally surrounded the test areas. The diameter of the outer fence was 140 feet, while the inner fence diameter was 85 feet; the height of each fence was 20 feet. A 150-ft^2 fire pit was located in the center of the test site.

1. 75-ft^2 3-D Environmental Fires

The 75-ft^2 3-D fire tests were conducted in the modified 150-ft^2 fire pit. These fire tests were designed to simulate an aircraft engine fire where the engine is attached to the under surface of an aircraft wing, a fuel line is broken, and the fuel is spilling from the engine onto the runway.

The simulation apparatus was constructed of barrels of two different sizes and welded one inside the other (Figures 2 and 3). The inner barrel was a standard 55-gallon drum with a diameter of 22.5 inches and a length of 36 inches. The outer drum was an overpack drum with a diameter of 33 inches and a length of 44 inches. The smaller drum was welded inside the larger barrel with support rods that kept the inner barrel centered within the outer barrel. This structure was suspended over the fire pit, with the front edge 15 degrees lower than the rear of the apparatus, on a fabricated swivel mount that was attached to a horizontal steel pipe boom. A fuel spray system was built into this apparatus to provide a constant supply of fuel for the tests.

A flexible fuel line was run from a pressured fuel pumping truck along the vertical and horizontal sections of the boom to a vertically-mounted multidirectional

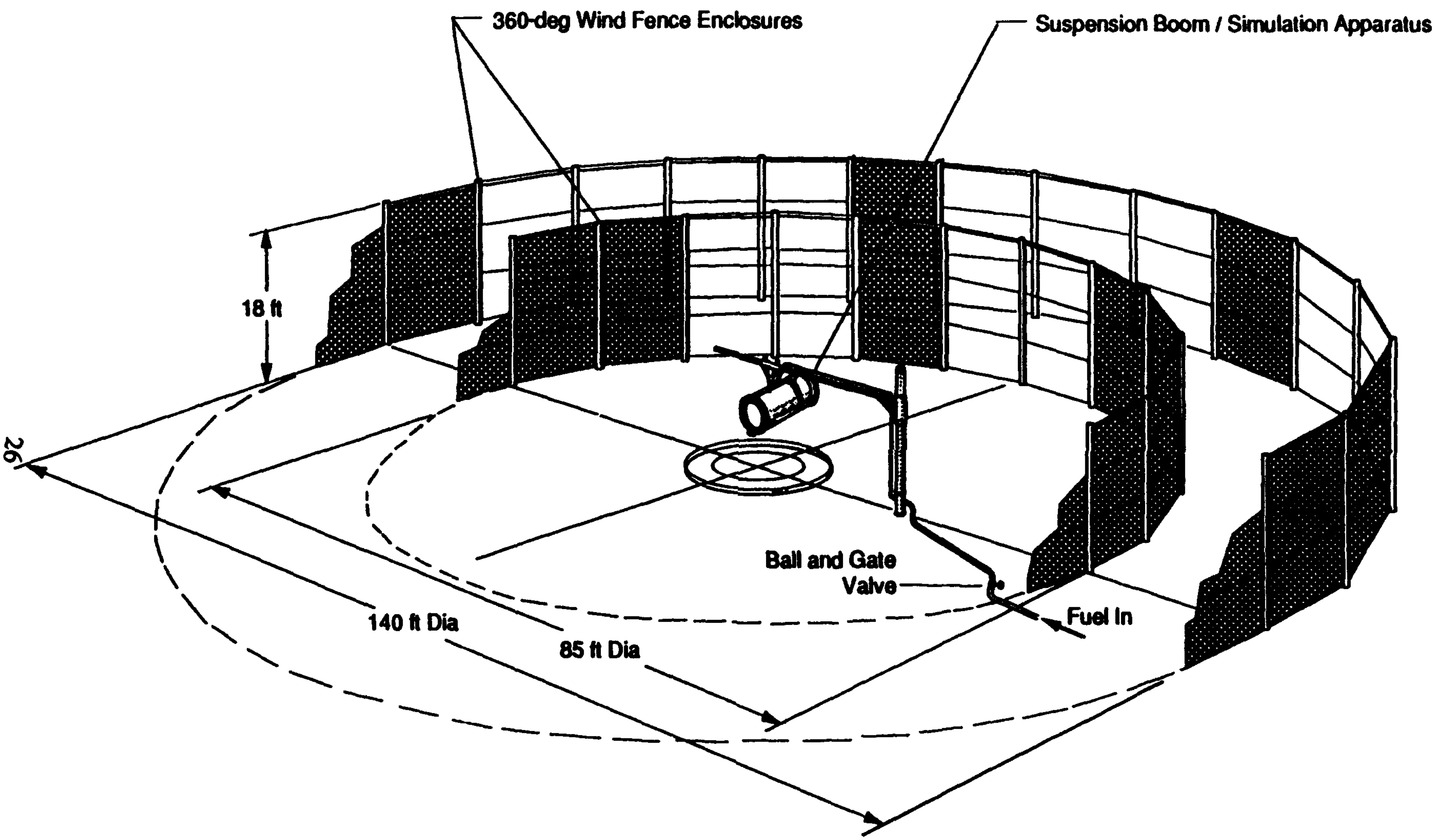

Figure 1. Wind Fence Enclosed Test Site.

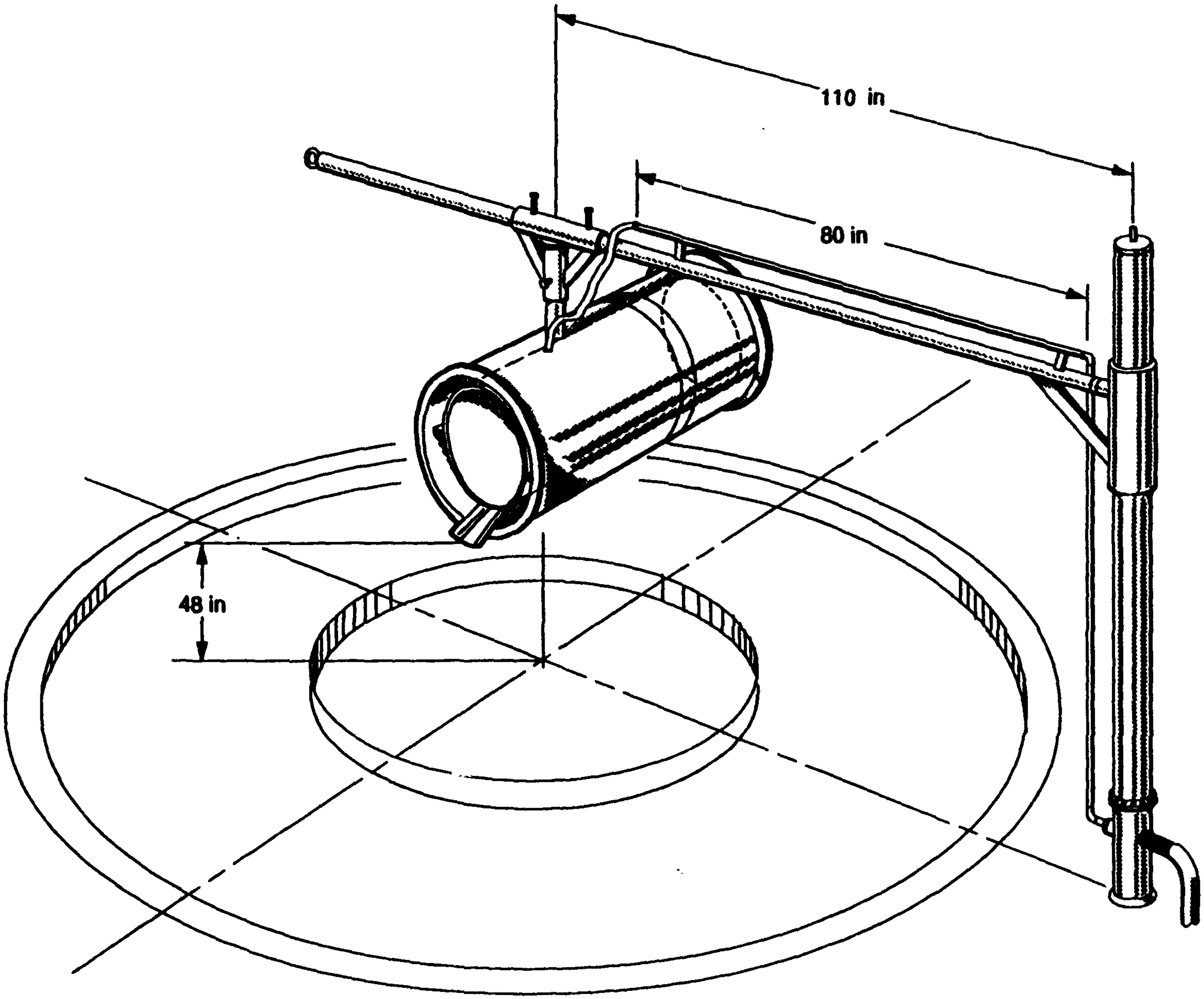

Figure 2. Three-Dimensional Running Fuel Apparatus.

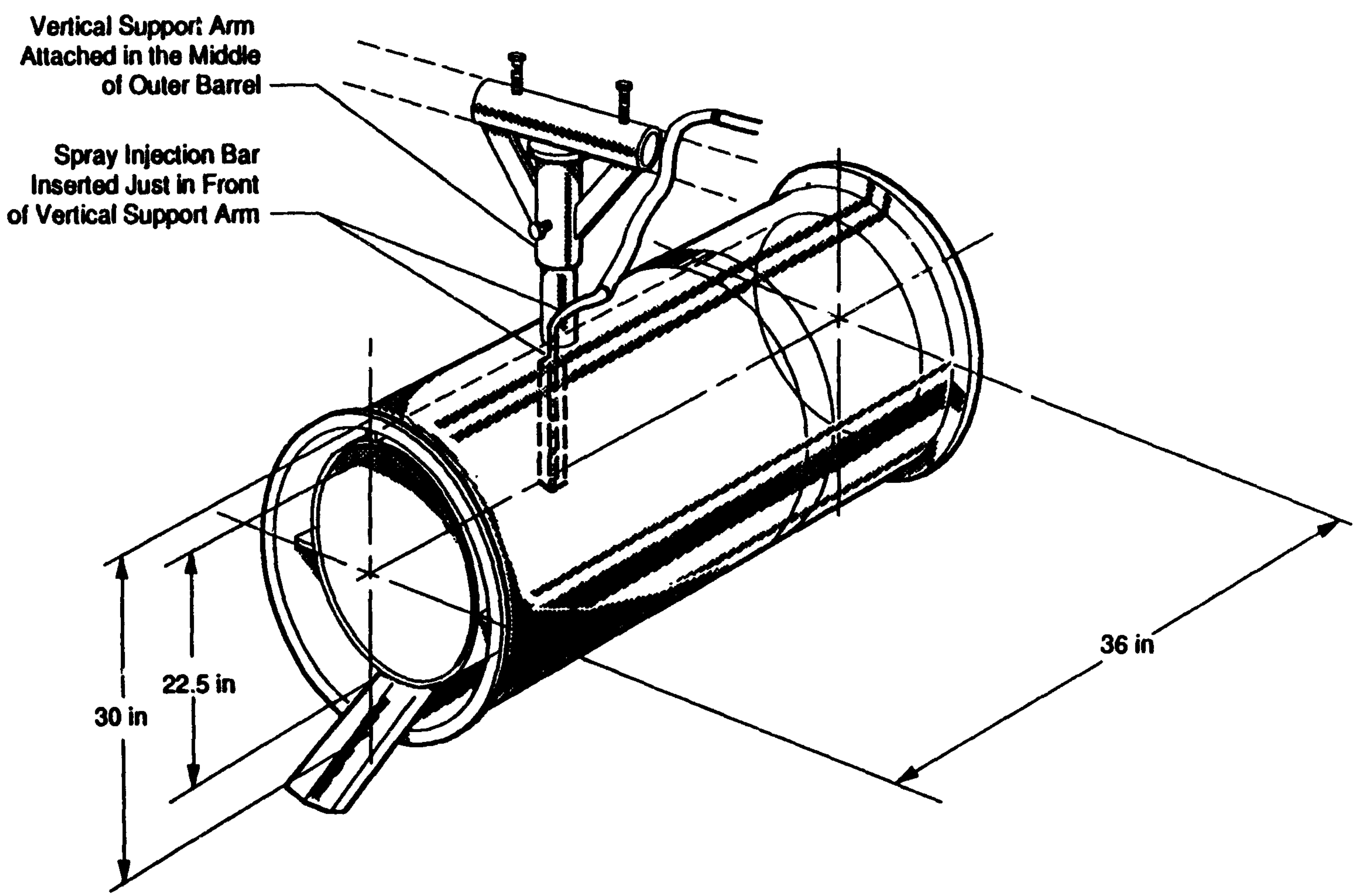

Figure 3. Detail of Three-Dimensional Running Fuel Apparatus .

spray bar inside the inner barrel that was shielded so that the fuel was sprayed toward the front, or lower end, of the apparatus. The fuel was sprayed into the inner barrel and a portion of the fuel flowed into the outer barrel through circular holes cut into the bottom of the inner barrel. The remainder of the fuel flowed the length of the inner barrel, into the overlapped edge of the outer barrel, and out of the apparatus into the circular fire pit located 4.5 feet below the apparatus. Fuel flow was regulated at an average rate of 3.0 to 3.5 gallons/minute.

The circular fire pit was constructed of concrete with an asphalt sealant coating covering the inner surface of the pit. The pit was 14 feet 8 inches in diameter, 16 inches deep, and was filled with water until a 2- to 4-inch vertical freeboard space remained. A metal circular containment ring (16 inches tall) was placed in the center of the pit to contain the fuel to a 75-ft^2 surface area.

Ambient wind conditions were used to satisfy the environmental testing conditions. A Simerl Instrument (Sims 9668 Sky Special Model SS) three-cup anemometer was used to measure the wind speed; a 15-mph wind sock indicated wind direction.

2. Aircraft Wheel Gear/Hydraulic Oil Fires

The apparatus used for these tests included an actual landing gear assembly from a fighter aircraft mounted in a vertical position in a fire pan (Figure 4). The landing gear assembly was complete and consisted of the tire, wheel, brakes, and the landing strut and supporting braces. This assembly was mounted in a vertical position by using steel support angles welded to the assembly and the fire pan. The fire pan was constructed of steel, had a diameter of 6 feet, and a depth of 4 inches. A section of 1/4-inch stainless steel tubing was used to simulate a broken hydraulic oil line. This line was mounted where the actual hydraulic line would be located. On one end of this tubing, a spray nozzle was attached to disperse the hydraulic oil in a flat spray pattern. The nozzle flow was directed toward the brake housing and the tire. The other end of the tubing was connected to a pressurized cylinder containing military-

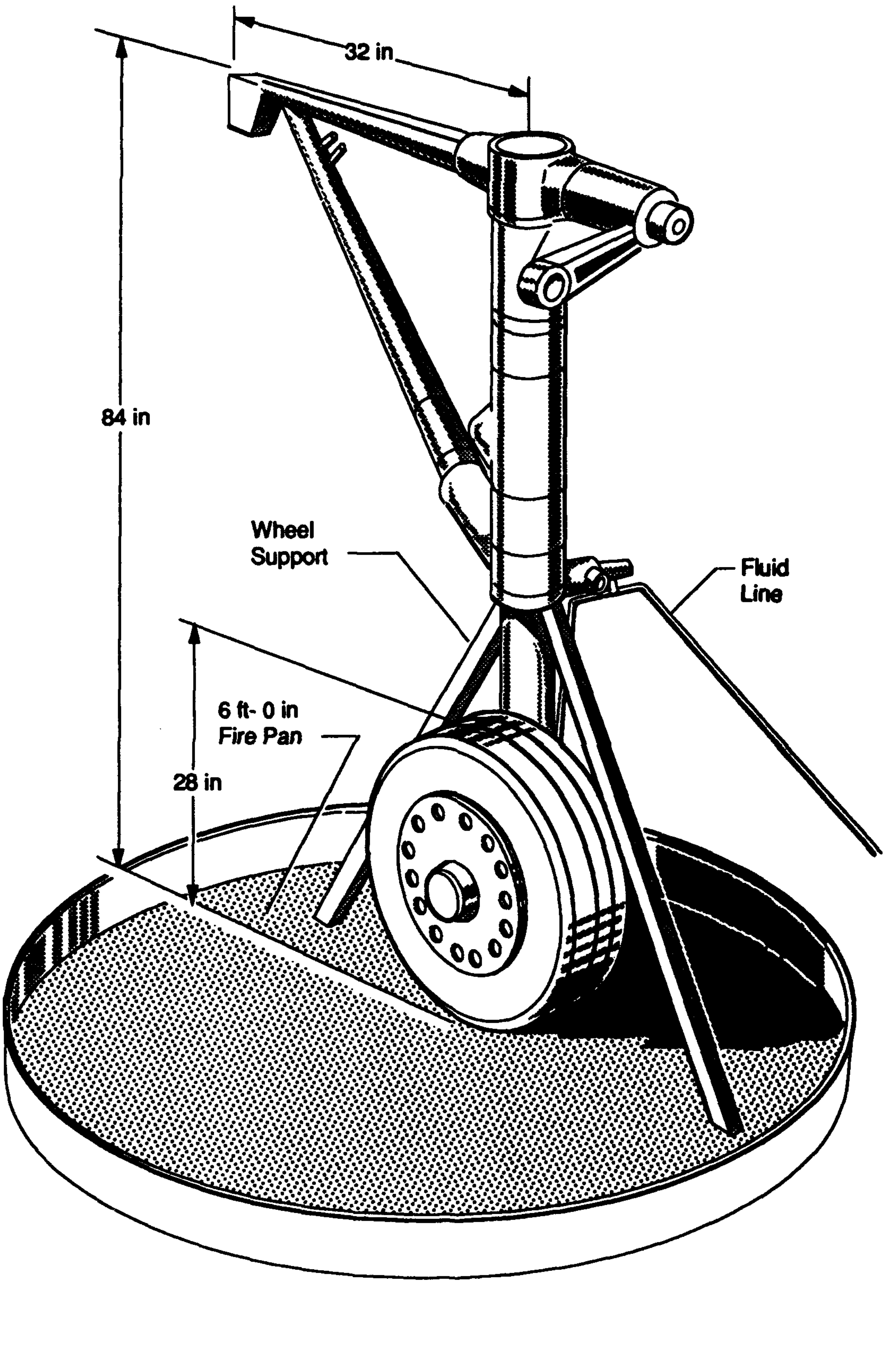

Figure 4. Aircraft Wheel Gear/Hydraulic Oil Fires Apparatus.

grade hydraulic oil. This cylinder was mounted vertically with a constant pressure source attached to the top of the cylinder and an electrically actuated solenoid valve connected to the bottom. The tubing was connected to this solenoid valve.

3. Semienclosed Electric Motor Fires

A 11-ft^3 semienclosed steel box structure was used for these tests (Figure 5). A removable lid partially covered the opening at the top of this box during the test. A 1/2-horsepower, 115-volt electric motor was used for each test (Figure 6). During the testing the motors were mounted on the interior floor of the box. The thermal overload switches on the motors were disabled, and the motor shafts were immobilized so that the motors would overheat when electrical power was applied.

4. Semienclosed Oxygen-Enriched Fuel Fires

The same 11-ft^3 semienclosed steel box used in the electrical motor test was used for the oxygen-enriched fuel fire tests (Figure 7). The lid for the box was completely closed during these tests. An 18-inch diameter, 4-inch deep fire pan was filled with jet fuel to a depth of ½ inch for these tests. A ¼-inch stainless steel tubing section was connected to an oxygen supply cylinder via an oxygen welding hose and a flash arrestor valve. The free end of this tubing was positioned so the oxygen would flow directly into the fire in the fire pan. The oxygen flow was regulated at a constant flowing pressure during these tests.

C. EQUIPMENT AND MATERIALS

As required by the Test Concept Paper (Reference 3), the jet fuel used for all testing was Jet-A, the commercial equivalent of military JP-8. These two fuels are essentially the same and can be used interchangeably for fire testing. Jet-A was used because military JP-8 was unavailable for these tests.

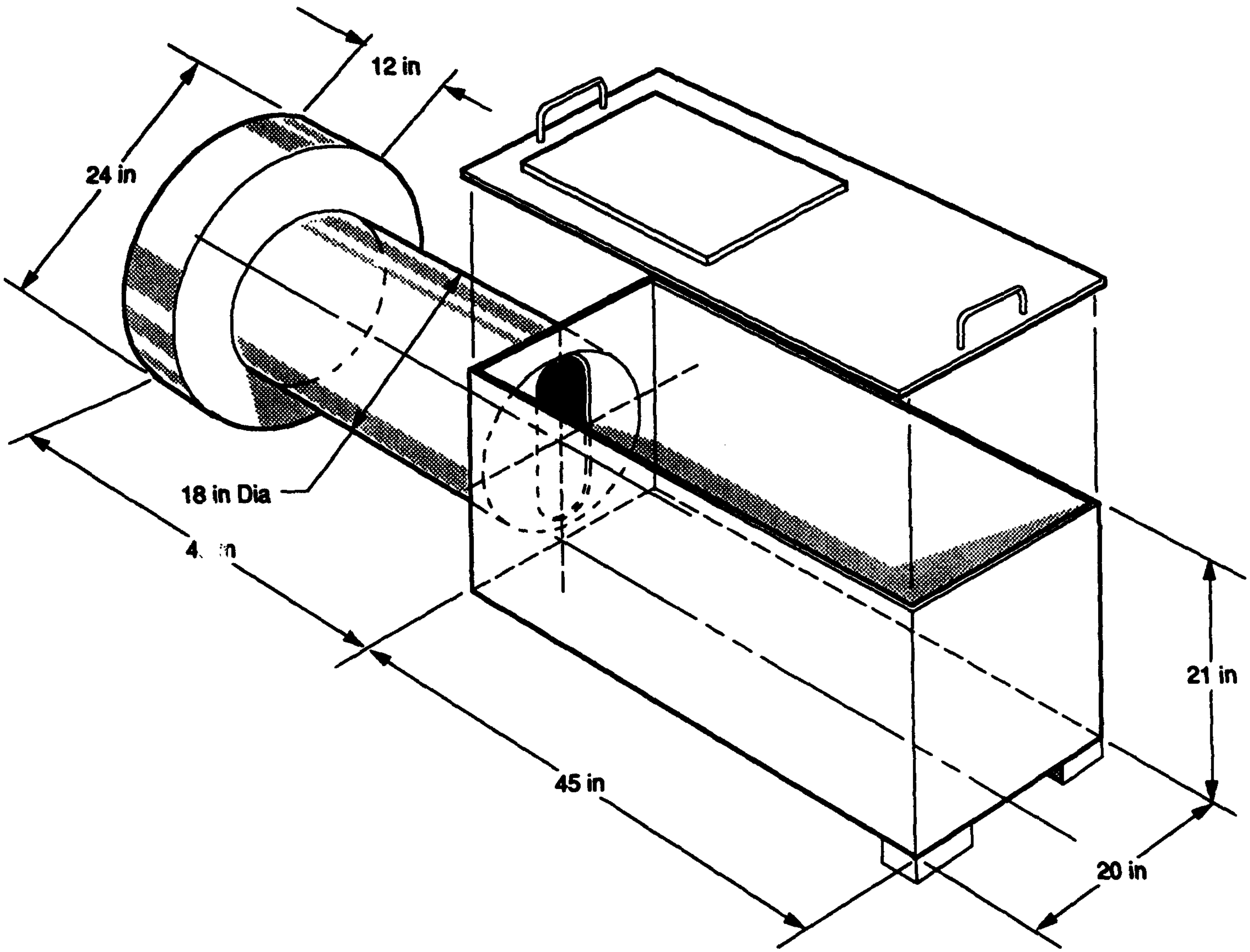

Figure 5.   Fire Enclosure, Overall View.

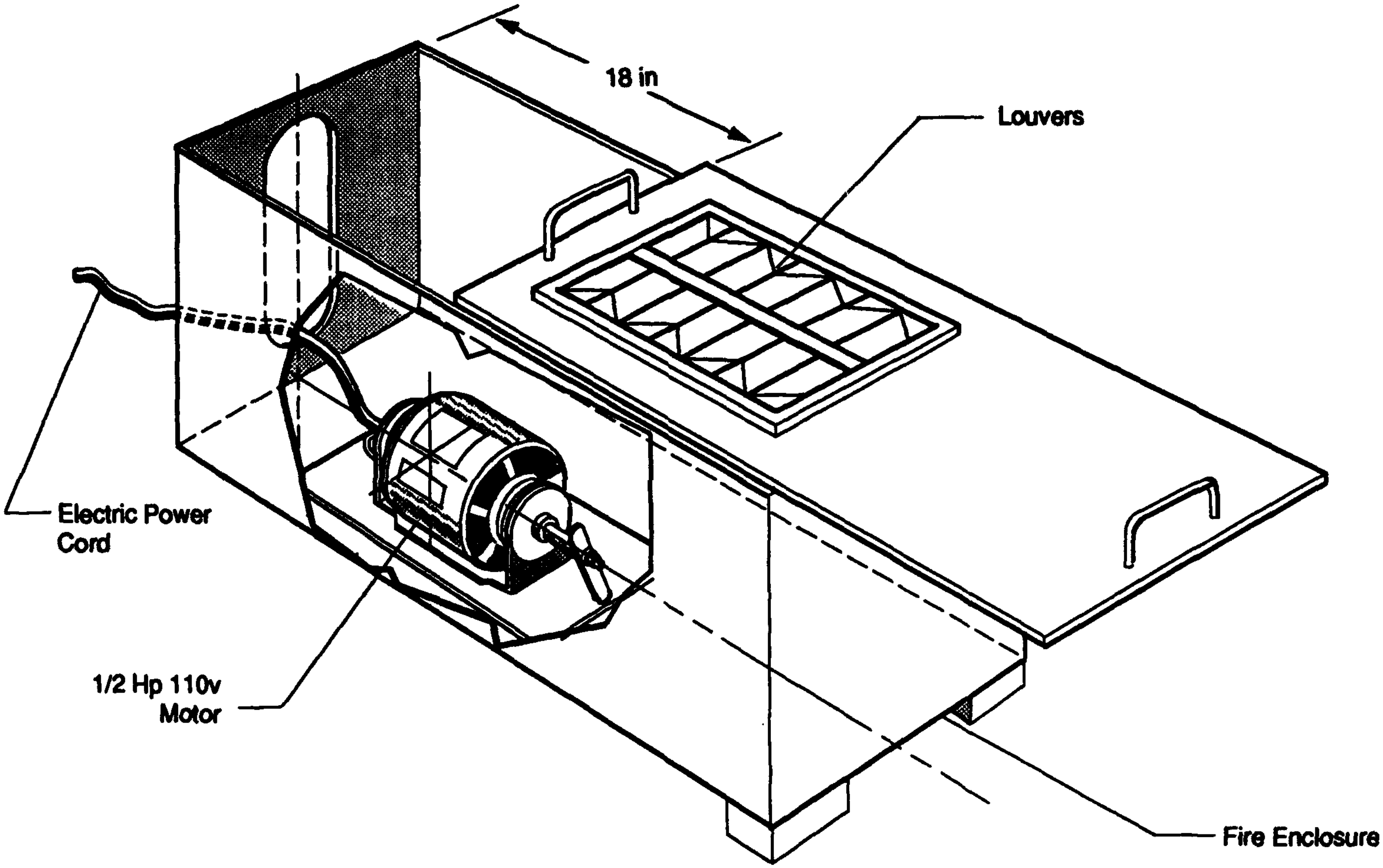

Figure 6. Electric Motor Apparatus.

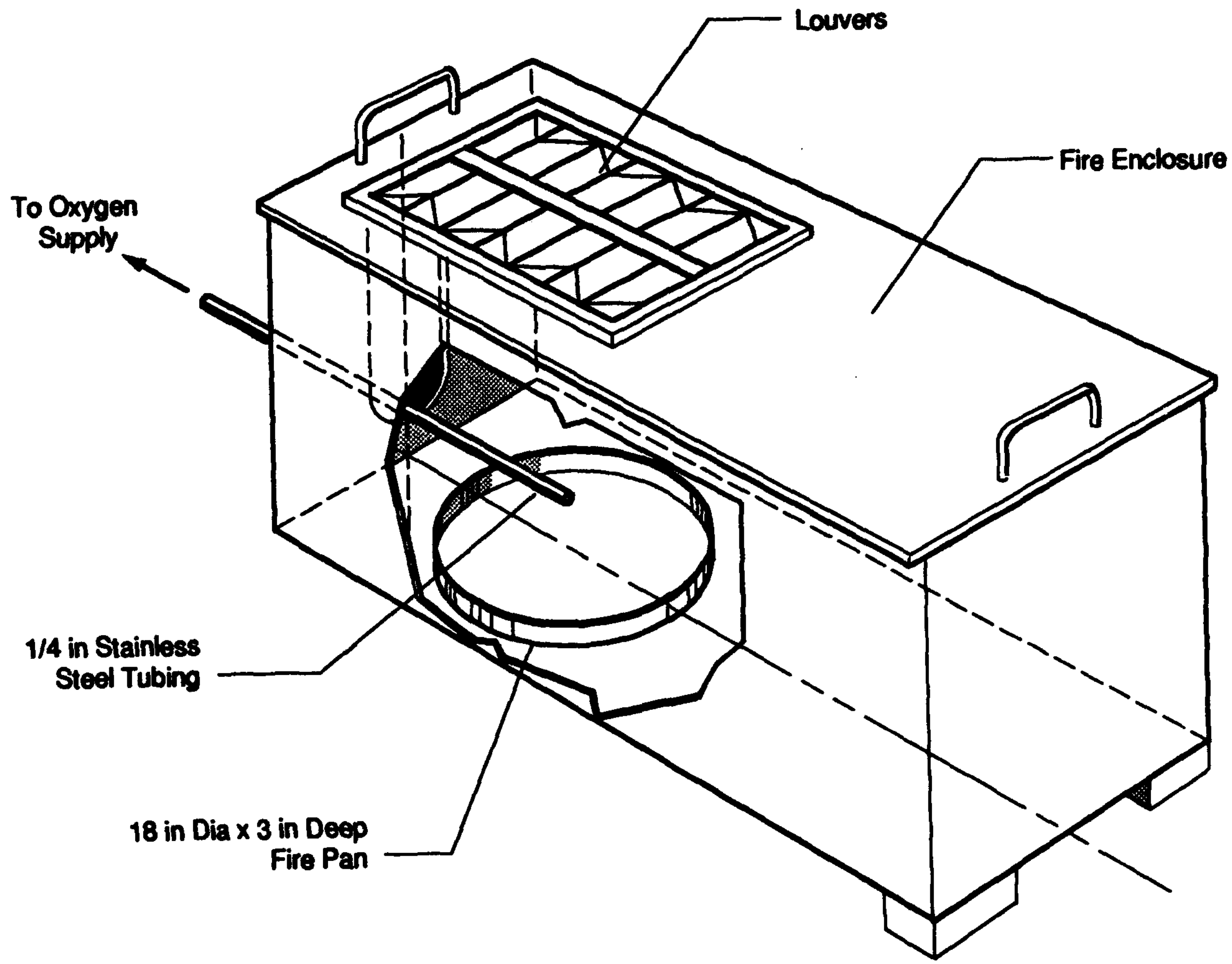

Figure 7. Oxygen Test Apparatus.

The extinguishers used in this testing were standard Amerex Mod. 372 20-pound handheld and Mod. 600 150-pound wheeled flightline units. These units were filled with either Halon 1211 or perfluorohexane pressurized to 200 $lb/in.^2$. Standard Amerex and Spraying Systems nozzle types were connected to the agent hoses and used in the testing. The Spraying Systems nozzles were used to maximize the performance of the perfluorohexane with the 150-pound extinguishers. These Spraying Systems nozzles (Model 25750 flat spray and Model 15630 full cone spray) produce the high agent flow rate and slightly dispersed spray pattern required to optimize the performance of perfluorohexane.

D. TEST PROCEDURES

These tests were conducted in accordance with the guidelines provided in the Test Concept Paper. As required, a total of 4 tests, 3 with perfluorohexane and 1 with Halon 1211, were conducted for each series of tests. The limitation of the number of tests was caused by the cost and limited availability of the perfluorohexane and the environmental impact of the Halon 1211 to the stratospheric ozone.

1. 75-ft^2 3-D Environmental Fires

Six sets of environmental tests were conducted in which the 75-ft^2 3-D running fuel apparatus was used. The different environmental conditions required for these test sets were calm wind conditions, 10-mph tailwind, 10-mph crosswind, 1-inch/hour rainfall, and conditioning the extinguisher at -40 °F and 120 °F. Each of these test sets was conducted with the same test procedures to provide a performance comparison between perfluorohexane and Halon 1211. The 150-pound extinguishers fitted with the Spraying Systems Model 25750, flat spray nozzle for perfluorohexane and the standard flightline nozzle for Halon 1211 were used in this testing.

The testing procedure began by flowing jet fuel at a constant rate (3.0 to 3.5 gallons/minute) through the apparatus into the lower containing ring in the fire pit. The fuel flow was continued, and the containment ring was almost full of fuel when the fuel was ignited. The fire was then allowed to preburn for 10 seconds after all the fuel had been fully ignited and was vigorously burning. The firefighter, wearing full protective gear consisting of a self-contained breathing apparatus, approach fire suit and helmet, then approached the fire from the front, or upwind side. The agent was applied to the bottom fire first to knock down initially and then contain this fully involved fire before the upper barrel apparatus became unreasonably hot. Once the bottom fire was controlled, the agent stream was directed to the upper barrel fire, usually extinguishing this fire with one or two sustained bursts of agent. With the top fire extinguished, the firefighter then concentrated on extinguishing the remainder of the lower pool fire, usually finishing the extinguishment by applying agent to the remnant flammable fume fire located along the back edge of the containment ring. This entire extinguishing procedure was accomplished in 6 to 24 seconds. Once the fire was completely extinguished, the fuel flow was terminated and the test was completed. The remaining fuel left in the bottom containment ring was reignited and burned off; the upper apparatus was cooled with water after each test to maintain consistent testing conditions.

The tests in calm conditions were conducted using the wind abatement fencing to ensure calm wind conditions during the testing period. These fires were used as a baseline comparison test where ideal conditions prevailed. The data from the other environmental tests were evaluated by comparison with these ideal conditions data. The tests were conducted using the standard firefighting approach and extinguishing procedure.

The crosswind and tailwind tests were conducted without the use of the wind abatement curtains. These tests relied on ambient wind conditions to produce the desired wind effects for the tests. The winds were measured with a three-cup anemometer to ensure the required wind intensity was maintained during the testing period. During each of the types of tests, the firefighter approached the fire and applied the agent from the same direction as had been used for the calm condition fires.

The rainfall environmental tests were conducted with the same procedure and testing setup as the calm wind tests except that a fire hose was used to simulate the rainfall. A 1 ½-inch fire hose coupled to an adjustable water spray fire hose nozzle and supplied with 60 to 70 lb\in.^{2} of water was used to simulate the required 1 inch/hour rainfall conditions. The "rainfall" was calibrated by testing the nozzle and hose system before the actual fire tests. This measurement was accomplished by pointing the open nozzle upward at a 45° angle, timing the water flow rate, and measuring the water collected in pans placed beneath the water spray during the calibration test. The water stream and water flow rate from the nozzle were adjusted during these calibration tests to produce the required "rainfall" rate.

Several extra procedures and equipment were required to conduct the cold extreme (-40 °F) conditioning fire test. First, the 150-pound extinguishers were fitted with sealed thermowells. These thermowells were fitted into the fill indicator gauge hole at the top of the extinguisher cylinder. They were made long enough to extend to within 6 inches of the bottom of the interior of the cylinder. Once the thermowells were installed, they were sealed with a silicone-base sealant to prevent leakage when the extinguisher was pressurized. This modification facilitated a direct interior agent, temperature measurement method when a thermocouple was slipped into the thermowell. Next, an environmental chamber was rented from Sandia National Laboratories (Kirtland Air Force Base) to precondition the extinguishers at -50 °F for 24 hours before the fire test. The interior extinguisher temperatures were read and recorded by computer during this conditioning period. Insulated shipping boxes, fitted to the dimensions of the extinguisher, were designed and constructed of 3/4-inch plywood and 2-inch styrofoam. Each extinguisher was fitted into its own shipping box, and the box was heavily wrapped in blankets as the extinguishers were transported the 1 ½ miles from the environmental chamber to the fire testing area. The extinguishers were quickly unloaded at the fire test area, the agent temperature was checked, and the fire tests were rapidly accomplished to minimize the possible rise in agent temperature before the test. The agent within each extinguisher was maintained at the -40 °F required temperature until the fire test was begun. These fire tests were conducted with the same procedures and testing setup as the calm wind tests.

Similar pretest and fire test procedures were used for the extreme-hot (120 °F) fire tests. The same insulated shipping boxes used in the extreme-cold fire tests were used for extinguisher temperature conditioning in the extreme-hot tests. However, instead of using the environmental chamber, each filled extinguisher was individually heated inside a sealed shipping box with a 250-watt infrared lamp pointed at the base of the extinguisher cylinder. This conditioning was continued overnight, and the extinguishers were tested the next morning. The interior temperature of the agent in each extinguisher was maintained at the required 120 °F temperature until the agent was released during the test. These fire tests were also conducted with the same procedures and testing setup as the calm wind tests.

2. Aircraft Wheel Gear/Hydraulic Oil Fires

These fires were conducted to simulate a hot brake fire in which a hydraulic line breaks and sprays hydraulic fluid onto the tire and hot brake assembly thus igniting the fluid. This causes the brakes, brake housing, and the tire to become engulfed in flames, and the tire begins to burn. To conduct this test, a 1-gallon vertically-mounted, pressure cylinder was filled with military-grade Shell Rotella 10 W hydraulic oil. Pressurized air at 120 $lb/in.^2$ was used to maintain a constant charge in the pressure cylinder throughout the test. An electrically-actuated valve attached to the bottom of the cylinder was activated to spray fluid onto the tire and brake assembly. This fluid was ignited and allowed to preburn for 50 seconds. The agent was then applied to the fire, and the fire was extinguished. The 150-pound extinguishers, fitted with the Spraying Systems Model 25750 flat spray nozzle for perfluorohexane and the standard flightline nozzle for Halon 1211, were used for these tests.

3. Semienclosed Electric Motor Fires

These tests were conducted by mounting a 1/2-horsepower, 115-volt, 7.6-amp electric motor to the interior floor of a semienclosed 11-ft^3 steel rectangular box container. A lid large enough to cover the top of the box entirely was partially removed for this test so that agent could be directly applied to the burning motor. Steel arms were welded to the shafts of the motors so the shaft was immobilized when the motor was running. The thermal protection switches were also disabled so the motor would heat to the ignition point when the shaft was immobilized. The jammed motor was allowed to smoke until it shorted and ignited, usually within 4 to 5 minutes after energizing the motor. After the motor was ignited, agent was applied through the top opening in the container, using a 20-pound extinguisher for each agent. A separate motor was used for each test.

4. Semienclosed Oxygen-Enriched Fuel Fires

The oxygen-enriched fuel fires were conducted in the same 11-ft^3 semienclosed steel container as the electrical motor fires. The lid to the container was completed closed for this test. The movable ventilation louvers on one end of the lid were opened to allow the fuel fire to maintain a maximum intensity. A 18-inch diameter fire pan was filled to a ½-inch depth with jet fuel for this test. The ½-inch depth of fuel was maintained for each test by checking the depth after each test and adding fuel if necessary. The fuel was ignited and allowed to preburn for 30 seconds before the oxygen was applied to the fire. The oxygen was then turned on and supplied to the fire at a constant 60 $lb/in.^2$ flowing pressure for another 30 seconds. The agents were then applied to the fire, while the oxygen was still flowing, by using an access pipe attached to the side of the containment box. The 150-pound extinguishers with the Spraying Systems Model 25750 nozzle for perfluorohexane and the standard flightline nozzle for Halon 1211 were used for these tests.

E. TEST RESULTS

1. 75-ft^2 3-D Environmental Fires

These tests were conducted to determine the effect of weather, or environmental conditions, on a typical flightline scenario fire. The fires were conducted using the same equipment and agent application techniques. The results from these fires were compared to the data from the fire tests conducted in calm or ideal conditions. All data obtained from these tests are presented in Table 8.

The calm condition tests were usually very intense and difficult to extinguish since the fire would quickly heat the upper barrel apparatus. However, the calm conditions also aided the application of the agent by allowing the agent to remain on the fire after it was applied, maximizing the effectiveness of the agent. During these tests, an average of 80 pounds of perfluorohexane was needed to extinguish the fires totally (Table 9). The average amount of Halon 1211 for these tests was 21 pounds. When the effectiveness of the two agents is compared, it is apparent that 3.8 times more perfluorohexane is necessary for extinguishment. Presumeably, this disparity in required agent amounts could be narrowed with further nozzle testing and refinement.

The crosswind and tailwind tests were more difficult to extinguish than the calm condition fires because the winds swept the agent away from the fire as it was being applied, which minimized the concentration of agent on the fire. This minimizing effect influenced the performances of both perfluorohexane and Halon 1211 in a similar manner. In the crosswind tests, averages of 95 pounds of perfluorohexane and 24 pounds of Halon 1211 (a ratio of 3.9 to 1) were necessary for extinguishment, an increase for both agents (Table 9). For the tailwind tests, averages of 102 pounds of perfluorohexane and 34 pounds of Halon 1211 (a of ratio 3.0 to 1) were necessary, again requiring an increase for both agents (Table 9). The winds affected both agents by reducing their effectiveness; however, the ratio of perfluorohexane to Halon 1211 agent amounts remained at approximately 3.6 to 1 throughout these tests. The effectiveness of the perfluorohexane was decreased by 17 percent (crosswind conditions) and 26 percent (tailwind conditions). The effectiveness of the Halon 1211 was decreased by 14 percent (crosswind conditions) and 62 percent (tailwind conditions). During the crosswind tests, the effectiveness of the two agents was almost equally affected; however, in the tailwind tests, the effectiveness of Halon 1211 was further decreased by 36 percent. Therefore, the winds seemed to affect the performance of Halon 1211 more than that of perfluorohexane.

TABLE 8. COMPARISON OF ENVIRONMENTAL CONDITION TESTING.

	Calm Wind Conditions	Crosswind (10 mph)	Tailwind (10 mph)	Rain (1 in/hr)	Extreme Cold (-40 °F)	Extreme Heat (120 °F) Series A	Extreme Heat (120 °F) Series B1	Extreme Heat (120 °F) Series B2
<u>Perfluorohexane</u>[a]								
Amount of agent used (lbs)	80.7	94.7	101.8	75.7	41.3	133.0	93.0	81.0
Time to extinguishment (sec)	15.2	18.2	19.9	13.7	7.8	29.6	19.3	16.3
Agent flow rate (lbs/sec)	5.3	5.3	5.2	5.5	5.3	4.5	5.0	5.0
Preburn period (sec)	10	10	10	10	10	10	10	10
Nozzle type	Veejet 25750	Veejet 25750	Veejet 25750	Veejet 25750	Veejet 25750	Veejet 25750	Veejet 25750	Full Jet 15630
Fire extinguishment ratio (% extinguished)	100	100	100	100	100	33	100	100
<u>Halon 1211</u>								
Amount of agent used (lbs)	21.0	24.0	34.0	15.0	16.5	17.0	24.0	---
Time to extinguishment (sec)	6.0	9.0	13.4	8.5	6.3	5.4	8.2	---
Agent flow rate (lbs/sec)	3.5	2.7	2.5	1.8	2.6	3.0	2.9	---
Preburn period (sec)	10	10	10	10	10	10	10	---
Nozzle type	Std.Flightline	Std.Flightline	Std.Flightline	Std.Flightline	Std.Flightline	Std.Flightline	Std.Flightline	
Fire extinguishment ratio (% extinguished)	100	100	100	100	100	100	100	

[a]Average of three tests.

TABLE 9. WIND CONDITION AGENT VALIDATION TESTS.

	Calm Conditions	Crosswind (10 mph)	Tailwind (10 mph)
Perfluorohexane[a]			
Amount of agent used (lbs)	80.7	94.7	101.8
Time to extinguishment (sec)	15.2	18.2	19.9
Agent flow rate (lbs/sec)	5.3	5.3	5.2
Preburn period (sec)	10	10	10
Nozzle type	Veejet 25750	Veejet 25750	Veejet 25750
Halon 1211			
Amount of agent used (lbs)	21.0	24.0	34.0
Time to extinguishment (sec)	6.0	9.0	13.4
Agent flow rate (lbs/sec)	3.5	2.7	2.5
Preburn period (sec)	10	10	10
Nozzle type	Std. Flightline	Std. Flightline	Std. Flightline

[a]Average of three tests.

The rainfall tests reduced the difficulty of extinguishing the fire for both agents. Although the fire was not visually less intense than the calm condition fires, the cooling effect of the rain did improve the effectiveness of both agents. Averages of 76 pounds of perfluorohexane and 15 pounds of Halon 1211 were necessary for extinguishment (a ratio of 5.0 to 1) (Table 10). The rain seemed to improve the effectiveness of the Halon 1211 to a greater degree, with an increase in effectiveness of 29 percent. The increase in the performance of the perfluorohexane was less, with an increase of only 6 percent.

TABLE 10. AGENT VALIDATION TESTING, RAINY CONDITIONS.

	Perfluorohexane[a]	Halon 1211
Amount of agent used (lbs)	75.7	15.0
Time to extinguishment (sec)	13.7	8.5
Agent flow rate (lbs/sec)	5.5	1.8
Preburn period (sec)	10	10
Nozzle type	Veejet 25750	Std. Flightline

[a]Average of three tests.

The performance of the perfluorohexane greatly increased when it was tested at the cold temperature extreme of -40 °F. The agent was expelled from the nozzle in large droplets not seen before in the ambient temperature testing. This spray pattern, coupled with the temperature of the agent itself, was responsible for quickly knocking down and extinguishing the fire. Averages of 40 pounds of perfluorohexane and 17 pounds of Halon 1211 (a ratio of 2.5 to 1) were necessary for extinguishment (Table 11). This was a slight increase (19 percent) for Halon 1211 effectiveness but was a large increase for the perfluorohexane (51 percent). The perfluorohexane was a more effective extinguishing agent at these low temperatures than in the normal test conditions.

TABLE 11. AGENT VALIDATION TESTING, EXTREME COLD (-40 °F).

	Perfluorohexane[a]	Halon 1211
Amount of agent used (lbs)	41.3	16.5
Time to extinguishment (sec)	7.8	6.3
Agent flow rate (lbs/sec)	5.3	2.6
Preburn period (sec)	10	10
Nozzle type	Veejet 25750	Std. Flightline

[a]Average of three tests.

Two sets of extreme-heat temperature (120 °F) tests were conducted as a result of the problems presented by the results of the first series of tests. The data are represented in Table 12 as Series A for the first test series (3 with perfluorohexane and 1 with Halon 1211), Series B1 for the first three tests of the second test series (2 with perfluorohexane and 1 with Halon 1211), and Series B2 for the last test in the second test series (1 test with perfluorohexane).

TABLE 12. AGENT VALIDATION TESTING, EXTREME HEAT (120 °F).

	Series A	Series B1	Series B2
Perfluorohexane[a]			
Amount of agent used (lbs)	133.0	93.0	81.0
Time to extinguishment (sec)	29.6	19.3	16.3
Agent flow rate (lbs/sec)	4.5	5.0	5.0
Preburn period (sec)	10	10	10
Nozzle type	Veejet 25750	Veejet 25750	Veejet 25750
Halon 1211			
Amount of agent used (lbs)	17.0	24.0	---
Time to extinguishment (sec)	5.4	8.2	---
Agent flow rate (lbs/sec)	3.0	2.9	---
Preburn period (sec)	10	10	---
Nozzle type	Std. Flightline	Std. Flightline	---

[a]Average of 3 tests for Series A, average of 2 tests for Series B, and 1 test for Series B2.

In the first test series (Series A), the Spraying Systems Model 25750 nozzle, the nozzle used with perfluorohexane throughout the testing program, was again used with the 150-pound extinguishers. However, when the perfluorohexane was heated to the required temperature of 120 °F, this nozzle produced a spray pattern that was more gaseous than in the ambient temperature tests and resulted in a decrease in the effective throw range of the agent stream, making it difficult to extinguish the entire fire totally. During Series A, the firefighter could totally extinguish the upper barrel fire and control the bottom fire to where only approximately 1 to 5 percent of the fire remained, lingering on the back edge of the containment ring. This back edge fire could not be consistently extinguished because the throw range of the agent was decreased by the gaseous spray pattern. Only one out of three fires could be totally extinguished by the perfluorohexane, and this extinguishment required 133 pounds of agent. The increase in agent temperature did not adversely influence the effectiveness of the Halon 1211. Only 17 pounds of this agent were required to extinguish the fire (an effectiveness increase of 19 percent).

To verify these data, a second series of tests was conducted that were identical to the first series. In this test series (Series B), the effectiveness of the perfluorohexane improved for the first test, where 60 pounds of agent were required to extinguish the fire. However, in the second test with perfluorohexane, the effectiveness of the perfluorohexane again decreased, and 126 pounds of agent were required for fire extinguishment. Both fires were extinguished and in both cases the Spraying Systems Model 25750 nozzle was used, producing the same gaseous agent stream as in the Series A tests. These results proved that the 25750 nozzle could not be effectively used for this type of test at these elevated temperatures, so a second nozzle was tried with the perfluorohexane. The Spraying Systems Model 15630 was a full-cone spray nozzle designed to reduce slightly the agent flow rate but condense the agent stream into more of a straight stream. The Model 15630 nozzle had been tested previously in a test series with perfluorohexane in a 75-ft^2 3-D fire and had not been effective; however, a removable vane was found inside the nozzle, which was breaking up the agent stream and reducing its effectiveness. Once the vane was removed from the nozzle, the effectiveness of the perfluorohexane dramatically improved. When the final test of Series B (B2) was conducted, this nozzle (with the vane removed) was used and the fire was extinguished with 81 pounds of perfluorohexane. The same effectiveness had been achieved in the calm condition tests. Halon 1211 was also retested in Series B (B1), and its effectiveness decreased by 14 percent from the standard calm condition data; 24 pounds of agent were required for extinguishment. The change in the nozzle for the perfluorohexane improved the performance of the agent by almost 40 percent under the elevated temperature conditions and solved the effectiveness problem for this agent at this temperature.

2. Aircraft Wheel Gear/Hydraulic Oil Fires

These tests were conducted to determine the effectiveness of the agents with a hot brake and tire fire, a common occurrence on a flightline. The 150-pound extinguishers with the Spraying Systems Model 25750 nozzle for perfluorohexane and the standard flightline nozzle for Halon 1211 were used.

Both agents could effectively control and rapidly extinguish these fires. The fires were allowed to reach maximum intensity, after the hydraulic oil had been sprayed on the tire and brake assembly, and allowed to accumulate in the fire pan at the base of the tire. The tire itself was fully involved in the fire when the agent was applied. Averages of 16.7 pounds of perfluorohexane and 5.5 pounds of Halon 1211 (a ratio of 3.0 to 1) were necessary for fire extinguishment (Table 13). This ratio is roughly the same as that determined for the 75-ft^2 environmental test fires.

TABLE 13. AGENT VALIDATION TESTING, AIRCRAFT WHEEL GEAR/HYDRAULIC OIL.

	Perfluorohexane[a]	Halon 1211
Amount of agent used (lbs)	16.7	5.5
Time to extinguishment (sec)	4.9	3.1
Agent flow rate (lbs/sec)	3.5	1.7
Preburn period (sec)	50	50
Nozzle type	Veejet 25750	Std. Flightline
Extinguisher type	150-lb Amerex	150-lb Amerex

[a]Average of three tests.

3. Semienclosed Electric Motor Fires

These tests proved that both agents were effective against electrical fires, especially fires that are semienclosed. In these tests, averages of 2.7 pounds of perfluorohexane and 2.0 pounds of Halon 1211 were required for extinguishment of the fires (Table 14), which shows that both perfluorohexane and Halon 1211 have roughly the same effectiveness for this type of fire. Handheld 20-pound extinguishers were used for these tests so that the performance of the agent could be more thoroughly studied. The larger, 150-pound extinguishers would have delivered more agent to the fire than would be necessary for effective extinguishment.

No arcing or conductivity problems were observed when using either agent. In fact, it should be noted that the perfluorohexane caused a motor to cease arcing when the agent was applied to an electric motor. Perfluorohexane has been proven to be a nonconducting agent by its manufacturer, 3M Corporation, which used standard ASTM D 257 test methods to measure the resistivity of the fluid (Reference 4). This resistivity, 1.0×10^{15} ohm-cm, is quite low when compared to other standard materials (Table 15) (Reference 10).

TABLE 14. AGENT VALIDATION TESTING, SEMIENCLOSED ELECTRIC MOTOR.

	Perfluorohexane[a]	Halon 1211
Amount of agent used (lbs)	2.7	2.0
Time to extinguishment (sec)	9.1	2.8
Agent flow rate (lbs/sec)	0.3	0.7
Preburn period (min)	5.6	5.6
Nozzle type	0.234-in. Orifice	0.234-in. Orifice
Extinguisher type	20-lb Amerex	20-lb Amerex

[a]Average of three tests.

TABLE 15. RESISTIVITIES OF MATERIALS.

Material	Resistivity (ohm cm)
Perfluorohexane	1.0×10^{15}
Rubber	1.0×10^{21}
Mineral Oil	2.1×10^{13}
Copper	1.7×10^{-6}
Steel	$1.6\text{-}5.0 \times 10^{-5}$

4. Semienclosed Oxygen-Enriched Fuel Fires

This type of fire was designed to test safely the effectiveness of the agent on fuel fires, which are enriched, or intensified, by gaseous oxygen. The application of the oxygen caused the fire to become white-hot (indicating a increase in flame temperature), and a decrease in visible emissions was observed (an indication of more efficient combustion of the fuel). The 150-pound extinguishers with the Spraying Systems Model 25750 nozzle for perfluorohexane and the standard flightline nozzle for Halon 1211 were used in these tests.

Both of the agents were very effective in extinguishing these oxygen-enriched fuel fires. Averages of 4.3 pounds of perfluorohexane and 0.5 pounds of Halon 1211 were necessary to extinguish the fires (Table 16). This was a ratio of 8.7 to 1 and a significant increase from the ratio from the "standard" calm condition tests (3.6 to 1).

Both agents were greatly vaporized after application to the fire. Concentrating the agent inside the fire enclosure box caused this vaporization to occur. The agents reached their maximum atmospheric concentration level within the enclosure box, causing a heavy white cloud of agent to form. This cloud poured out of the enclosure box, spreading low to the ground for a distance of 10 to 20 feet after the extinguishment of the fire.

TABLE 16. AGENT VALIDATION TESTING, SEMIENCLOSED OXYGEN.

	Perfluorohexane[a]	Halon 1211
Amount of agent used (lbs)	4.3	0.5
Time to extinguishment (sec)	2.1	1.1
Agent flow rate (lbs/sec)	2.0	0.5
Preburn period, without oxygen (sec)	30	30
Preburn period, with oxygen (sec)	30	30
Nozzle type	Veejet 25750	Std. Flightline
Extinguisher type	150-lb Amerex	150-lb Amerex

[a]Average of three tests.

SECTION V
CONCLUSIONS

Several aspects need to be considered when developing evaluation tests for Halon 1211 replacement agents. Candidates must, as a minimum, be compatible with all materials that could be contacted in storage or operation, and must have acceptable extinguishment effectiveness properties. To verify that these conditions can be met for perfluorohexane, extensive testing was conducted. This testing established the materials compatibility and extinguishment capabilities under different fire scenarios for this agent.

The Materials Compatibility testing was conducted using standard test procedures. Standard testing methods outlined in ASTM standards were followed in the NMERI, Minnesota Rubber, and 3M Corporation testing. These tests showed that perfluorohexane is compatible with most materials.

3M Corporation, the chemical manufacturer of the perfluorohexane used in this testing program, suggested that BUNA-N nitrile-lined and reinforced butyl rubber hoses be used for extinguishers and transfer hoses (Reference 13). BUNA-N is also the recommended material for gaskets and seal materials. Teflon and silicone rubber are not recommended. However, Teflon sealant tapes used to wrap the threads of removable extinguisher parts should be acceptable.

Minnesota Rubber Co., the supplier of the extinguisher sealing elastomer materials used in the Air Force, also recommended that BUNA-N elastomers be used for extinguisher sealing materials (Reference 17). They mentioned that BUNA-N is currently the elastomer used for the Halon 1211 extinguishers and no retrofitting would be necessary to change to perfluorohexane, and that BUNA-N is by far the least expensive of the polymers they tested.

Considering these recommendations and the test results, BUNA-N should continue to be the elastomer material used for extinguisher seals, gaskets, and hoses if perfluorohexane is chosen as the replacement agent for Halon 1211.

The testing showed that perfluorohexane is also compatible with composite materials and electrical components that could be found on aircraft. This compatibility indicates that perfluorohexane should not degrade the condition of the aircraft materials, even if the agent remains in contact with the materials for an extended period of time.

The Agent Operational Validation tests were conducted to determine the effectiveness of perfluorohexane in comparison to Halon 1211. Tests were also conducted by the Air Force that maximized the performance of perfluorohexane by testing various nozzles or application methods. Since the effectiveness of the agent is highly dependent on the application method and the equipment used, these approved nozzles and methods were used in this testing.

In the Environmental testing series, several performance characteristics of perfluorohexane were defined and compared to those of Halon 1211. It was found that perfluorohexane was not as affected by winds as Halon 1211; however, the reverse was true under rainy conditions. The performance of perfluorohexane was slightly reduced in the rain while Halon 1211 performance was virtually unchanged. Also, the effectiveness of perfluorohexane dramatically improved when tested at -40 °F and degraded at 120 °F, while the Halon 1211 was unaffected. The effectiveness of the perfluorohexane at 120 °F was greatly improved when the application nozzle was changed from the flat spray to the full cone nozzle (interior vane removed).

Perfluorohexane, a nonconducting agent, was essentially as effective as Halon 1211 for semienclosed electrical fires. In fact, this agent disrupted the arcing of an electrical motor and prevented the arcing from recurring.

Perfluorohexane was also very effective on enclosed oxygen-enriched fires. Minimal amounts of agent were required to extinguish the fully involved oxygen-enriched fuel fires. However, Halon 1211 was more effective than the perfluorohexane. The oxygen-enriched tests also showed that when perfluorohexane was applied to an enclosed area, it formed a dense, ground-hugging agent cloud that was very effective in inerting a fuel surface and preventing reignition.

This testing showed that the effectiveness ratio between perfluorohexane and Halon 1211 for most tests was 3 - 3.6 to 1, thus indicating that perfluorohexane must be used in larger quantities during fire situations, or it must be reserved for first response use only.

This effectiveness ratio can probably be improved with further testing. The nozzle used throughout the testing should be changed to improve the overall agent performance, as demonstrated in the 120 °F environmental tests. More testing would improve the application techniques used with perfluorohexane; consequently, the testing of this agent should be continued to optimize its performance.

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